

Space geodetic constraints on fault slip rates and the distribution of aseismic slip on Bay Area faults

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Annual Project Summary for FY2004 Activities

This report covers the results from our geodetic investigations in the San Francisco Bay area to constrain fault slip rates and the distribution of aseismic slip. The work described was undertaken by the principal investigator, Roland Bürgmann, former graduate students David Schmidt and Matt d'Alessio and current graduate student Ingrid Johanson. The research is composed of collection and analysis of space geodetic data (GPS and InSAR) for fault-slip information, and modeling and interpretation of those results in the context of fault slip rates, the locked or aseismically creeping nature of individual segments of the southern Bay area fault system, and earthquake potential from those faults. Much of this work is contained in two manuscripts currently in review at the Journal of Geophysical Research, Schmidt et al. (2005) and d'Alessio et al. (2005).

1. Investigations Undertaken

The San Francisco Bay Area is a structurally complex region of the North American-Pacific plate boundary. We yearly occupy an extensive Global Positioning System (GPS) network in the Bay area and also incorporate data collected by the USGS. In the last two years, we have extended the network further into the creeping section of the SAF. The GPS data are integrated with other data sets such as the creepmeter records on the Hayward, Calaveras and San Andreas faults (Data collected by USGS, SFSU and CU Boulder). Interferometric synthetic aperture radar (InSAR) has been effectively integrated with GPS data to perform joint inversions for slip on the Hayward fault (Bürgmann et al., 2000; Schmidt et al., 2003; Schmidt et al., 2005). Although the use of InSAR in

the southern Bay Area has been hindered by large amounts of decorrelation noise (Johanson and Bürgmann, 2001), it has become a feasible data source through our implementation of a statistical-cost network-flow unwrapping algorithm and a novel data stacking approach (Johanson and Bürgmann, 2002). We are also incorporating subsurface slip rates on creeping members of the SAF system using repeating micro-earthquakes (e.g., Schmidt et al., 2005).

The primary objective of this project is to monitor the spatially and temporally complex active deformation field in the Bay Area. This report will focus on three aspects of this investigation:

- Status of GPS measured crustal deformation compiled in the BAVU GPS velocity field.
- Derivation of a block deformation model constrained by the BAVU GPS velocities
- The use of GPS, InSAR and repeating micro-earthquake data to detect and characterize the distribution of aseismic slip on the Hayward fault.

2. Results

GPS velocities in the Bay Area and block model

In an effort to put together the most comprehensive picture of crustal deformation in the San Francisco Bay Area, we have recently completed the Bay Area Velocity Unification (BAVU, “Bay View”) crustal motion map (D’Alessio et al., 2005). This study includes survey-mode GPS data from nearly 200 GPS stations throughout the greater San Francisco Bay Area from Sacramento to San Luis Obispo collected from 1991 to 2004 by U. C. Berkeley, the U.S. Geological Survey, the California Department of Transportation, Stanford University, U. C. Davis and the Geophysical Institute in Fairbanks, AK. These are combined with continuous GPS data from the Bay Area Regional Deformation (BARD) network. BAVU provides a consistent velocity field for monitoring fault slip and strain accumulation throughout the greater San Francisco Bay region.

We process survey-mode GPS data using the GAMIT/GLOBK software package. Along with the survey-mode data, we process five global stations from the International GPS Service (IGS) network and four to six nearby continuous stations from the BARD network. We combine daily ambiguity-fixed, loosely constrained solutions using the Kalman filter approach implemented by GLOBK. Within a given day, we include data processed locally as well as solutions for the full IGS and BARD networks processed by and obtained from SOPAC at the University of California, San Diego. The daily combined solutions are merged into monthly averaged solutions for time series and velocity estimation.

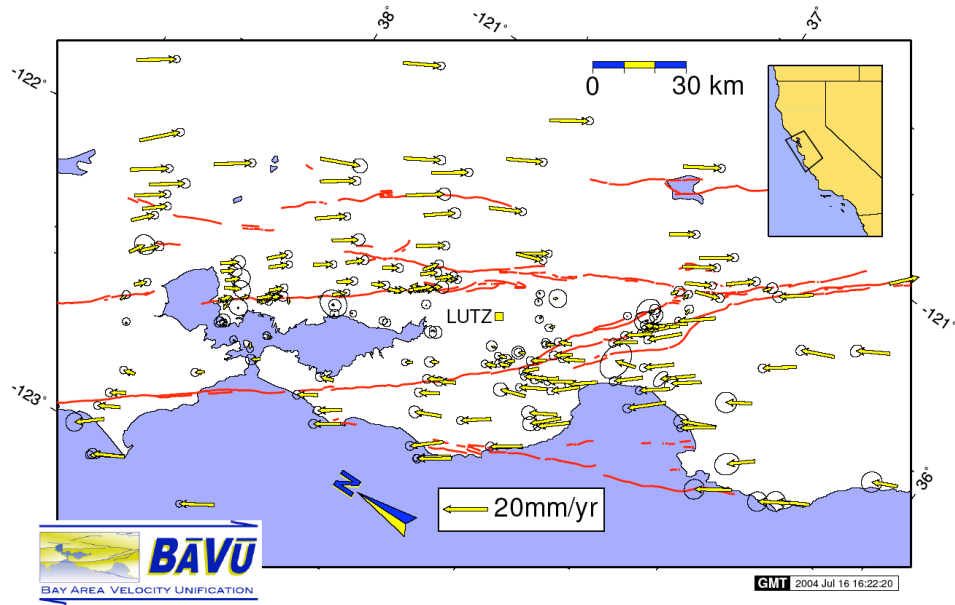


Figure 1. Map of the San Francisco Bay Area with GPS velocities from 1994-2003 relative to station LUTZ in the Bay Block from the BAVU study (d'Alessio et al., 2004). The map projection is about the estimated Pacific Plate–Sierra Nevada/ Great Valley pole of rotation

Figure 1 shows GPS velocities for the entire BAVU dataset relative to station LUTZ in the south Bay area. We use a block modeling approach (Meade et al., 2005) to estimate the angular velocity motions of fault-bounded blocks and strain accumulation rates on the faults that are most consistent with the observed surface velocities.

The total relative motion between the Pacific plate and the rigid Sierra Nevada/Great Valley (SNGV) microplate is $37.9 \pm 0.6 \text{ mm} \cdot \text{yr}^{-1}$ directed towards $\text{N}30.4^\circ \text{W} \pm 0.8^\circ$ at the latitude of San Francisco ($\pm 2 \text{ s}$). The Bay block, where LUTZ is located, shows up as a relatively undeformed block with many of the stations having velocities relative to LUTZ that are so small that they plot as dots in the figure. We find slip rates on the Bay Area faults are typically within the uncertainty of geologic estimates, although we also document substantial slip on segments that have not been emphasized in previous studies (Figure 2). Up to 4 mm/yr of strike-slip is permissible on the West Napa fault north of San Pablo Bay, which is consistent with geologic evidence showing that the some slip from the Calaveras fault is transferred westward. We find evidence for a fault along the eastern margin of the Coast Range, running parallel to the San Andreas through central California with 5 mm/yr of right-lateral slip and 3 mm/yr of fault-normal convergence. The Mount Diablo thrust system accommodates $3.9 \pm 0.5 \text{ mm} \cdot \text{yr}^{-1}$ of reverse-slip and $4.2 \pm 0.5 \text{ mm} \cdot \text{yr}^{-1}$ of right-lateral strike-slip and the San Gregorio fault carries $2.4 \pm 0.5 \text{ mm} \cdot \text{yr}^{-1}$. The total convergence across the Bay Area is negligible, though we observe localized shortening and extension. Poles of rotation for blocks within the Bay Area are located intermediate to the North America– Pacific and North America–SNGV poles with a systematic progression from west to east. The orientation of present-day relative plate motion cannot explain the strike of most Bay Area faults, but fault strike does

loosely correlate with inferred plate motions at the time each fault initiated. A detailed discussion of the BAVU results, which is beyond the scope of this annual report, has recently been submitted for publication (d'Alessio et al., 2005).

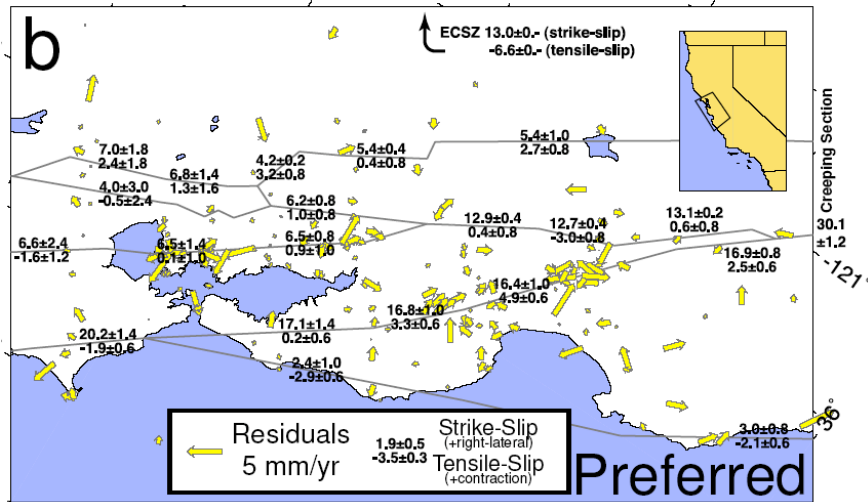


Figure 2. Difference between observed GPS velocities and model calculations for three different model scenarios. Numbers indicate strike-slip and tensile-slip rates and 95% (2) uncertainties for select fault segments. Positive strike-slip indicates right-lateral slip. Positive tensile-slip indicates contraction while negative tensile-slip indicates extension.

Aseismic slip along the Hayward fault

We solve for the slip-rate distribution on the Hayward fault by performing a least-squares inversion of geodetic and seismic data sets (Schmidt et al., 2005). Our analysis focuses on the northern 60 km of the fault. InSAR data from 13 independent ERS interferograms are stacked to obtain range-change rates from 1992 to 2000. Horizontal surface velocities of a subset of 141 BAVU sites are measured using GPS from 1994 to 2003. Surface creep observations and estimates of deep slip rates determined from characteristic repeating earthquake sequences are also incorporated in the inversion. The fault is discretized into 283 triangular dislocation elements that approximate the non-planar attributes of the fault surface (Figure 3). South of the city of Hayward, a steeply, east-dipping fault geometry accommodates the divergence of the surface trace and the micro-seismicity at depth. The inferred slip-rate distribution is consistent with a fault that creeps aseismically at a rate of ~ 5 mm/yr to a depth of 4 to 6 km. The InSAR data require an aseismic slip rate that approaches the geologic slip rate on the northernmost fault segment beneath Pt. Pinole while a low slip-rate patch of less than 1 mm/yr is inferred beneath San Leandro. We calculate that the entire fault is accumulating a slip rate deficit equivalent to a $M_w = 6.78 \pm 0.05$ per century. However, this estimate of potential coseismic moment represents an upper bound because we do not know how much of the accumulated strain will be released through aseismic processes such as afterslip.

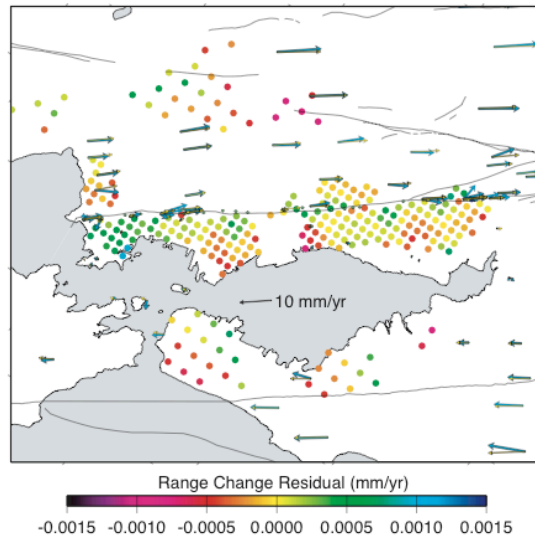
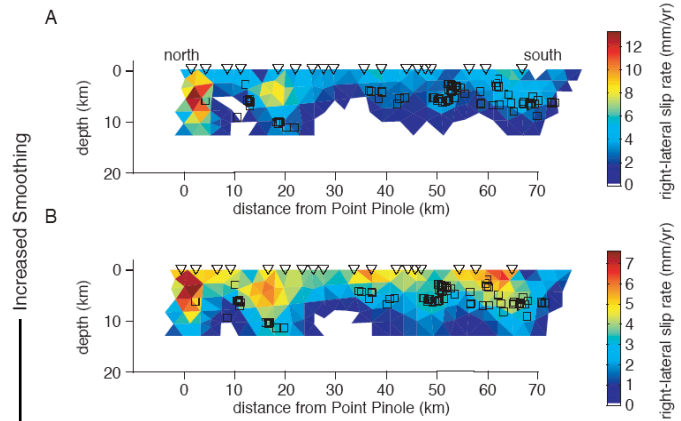


Figure 3. (A) Residual GPS-derived velocities (arrows) and InSAR-measured range change rates (color circles). The model includes regional deformation from deep dislocation below the San Andreas, Hayward, Calaveras and Greenville-Green Valley faults, and the distributed slip model from the joint inversion shown in (B).



(B) NW-SE section along the Hayward and Mission faults of distributed-slip inversion of regional GPS data, stack of InSAR range-change data, surface creep measurements and sub-surface aseismic slip rate estimates from repeating microearthquakes (from Schmidt et al., 2003 in prep.) The two panels show models with varying amounts of smoothing constraints.

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3. Non-technical Summary

We use the Global Positioning System (GPS) and Synthetic Aperture Radar Interferometry (InSAR) to gather information on crustal deformation and earthquake hazard in the San Francisco Bay region. The deformation data are used to determine a block model of regional deformation in the region, which provides information about fault slip rates and the rate of elastic loading of the major faults in the region. GPS and InSAR data about the Hayward fault are utilized to determine a detailed model of the distribution of locked and aseismically creeping portions of the fault in the subsurface. Despite significant creep on the fault in the upper 6 km, a slip deficit rate corresponding to as much as one M 6.8 per century is found.

4. Reports Published (2003 – 2004)

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6. Data Availability

Raw and RINEX formatted GPS data files for static surveys of markers in the San Francisco Bay area from 1994-2004. These files typically include greater than six continuous hours of data, recorded at a 30 s collection rate with a 10-degree elevation mask. These data are freely available through the UNAVCO archive facility in Boulder, and also at the University of California, Berkeley. http://archive.unavco.ucar.edu/cgi-bin/dmg/groups?cpn=1&oby=group_name Data collected by our group for this project are archived under the Group Names of “Calaveras Fault”, “Hayward Fault” and “Loma Prieta.”

Photocopies of survey log sheets and site descriptions are also available. Additional data used in this study included RINEX format files obtained from the U.S. Geological Survey and the Bay Area Regional Deformation Network (BARD). These files include campaign-style surveying (USGS) and continuous GPS stations (BARD) and are available at the NCEDC at UC Berkeley.

For more information regarding data availability, contact:

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InSAR data used in this project are available via the WInSAR archive, supported in part by the USGS.